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REFINEMENT OF CASTING TECHNIQUES FOR SMALL AIR-COOLED, TURBINE BLADES - PHASE I

General Electric Company
Aircraft Engine Group
Lynn, Mass. 01910

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Approved for public release; distribution unlimited.

Prepared for

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
Fort Eustis, Va. 23604

EUSTIS DIRECTORATE POSITION STATEMENT

This report provides the details of an effort to modify the design and to refine the casting procedures of the T700 Stage-two turbine blade to permit one-step casting and to reduce the cost. The results of this program exemplify the benefits that can be received by improving manufacturing processes for advanced engine components.

Mr. Jan M. Lane and Mr. A. Eugene Easterling, Propulsion Technical Area, Technology Applications Division, served as project engineers for this effort.

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T700 stage-two turbine blade was redesigned to permit application of advanced coring practices to investment cast turbine blades. The redesign resulted in a more producible turbine blade and reduced the overall cost of the blade. The design history, manufacturing steps, qualification procedures, engine test results and cost analysis are discussed for the radial-hole cooled turbine blade.

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PREFACE

USAAMRDL technical direction for the early portion of this program was provided by Mr. A.E. Easterling, while the latter portion was conducted under the direction of Mr. J.M. Lane. The principal investigator, program manager, and author of this study was Mr. G.S. Irons of General Electric.

Acknowledgement is given to Mr. L.R. Taber, T700 Design Engineering, and Mr. P.J. Wessells, Manufacturing Engineer, both of the General Electric Company, and to Mr. R.S. Jakus, Product Engineer at Misco Division of Howmet Corporation, all of whom contributed to the success of the overall program. This project was accomplished as part of the U.S. Army Aviation Manufacturing Technology Program. The primary objective of this program is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in the production of Army material.

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INTRODUCTION

All of the advanced aircraft engines currently being developed by General Electric Company, Aircraft Engine Group, use highly alloyed, gamma prime strengthened superalloys for the major hot rotating turbine components. The alloys of major interest for equiaxed turbine blades within General Electric are René 80, René 120, and René 125. While these alloys offer remarkable properties at elevated temperatures, the design of modern gas turbine engines requires that the gas generator turbine blades be cooled by various techniques. The usual practice is to cast the internal cooling passages where possible. When limited by such factors as section thickness and hole size, cast cooling passages are supplemented with machined cooling holes. The machining characteristics of these alloys and high length-to-diameter ratios of the cooling passages result in heavy dependence upon unconventional methods such as Electrical Discharge Machining (EDM), electrostream, Shaped Tube Electrolytic Machining (STEM), and laser drilling. These machining operations result in a higher cost component than achievable with cored passages only. There is little doubt that the cost effective application of turbine blade superalloys depends very heavily upon reductions in processing and associated labor costs. This objective can be achieved only through judicious selection of component design, coring practice and manufacturing technique.

The original T700 second-stage blade had complex coring and machining requirements that precluded attempts to cast the blade in one-step. The objective of this program was to develop coring techniques that minimized machining, improved producibility and reduced the cost of the T700 stage-two high-pressure turbine blade.

BLADE DESIGN

The original T700 stage-two blade design specified four radial-cored cooling holes, six drilled chordwise trailing-edge cooling holes, and a cast-in tip plenum cavity. This design is shown schematically in Figure 1 and will be referred to subsequently as the chordwise trailing-edge hole design. Value analysis of this design identified the drilling of the chordwise trailing-edge holes and the cross-pin braze closure of the stepped radial hole as significant manufacturing cost elements.

A program was initiated to reduce the cost of the stage-two blade by providing a means to one-step cast the blade, thereby eliminating the drilling of the trailing-edge cooling holes and the brazing of the cross-pin. A configuration was selected which had six radial holes spaced out to cool the blade cross section as shown in Figure 2. The additional cooling associated with the two added holes and the changed hole positions was expected to eliminate the necessity for electrostream drilling the chordwise trailing-edge holes, as well as for the cross-pin brazing operation. The one-step casting approach selected at the start of the program involved the use of quartz rods to form the radial cooling passages and a ceramic core to form the tip plenum cavity. Some problems were anticipated in the attachment of the quartz rods to the tip plenum core, and initially it was expected that the plenum would be produced through a combination of coring and EDM operations. This was changed as will be discussed in the tooling section of this report.

Heat Transfer Analysis

Based upon the proposed radial-hole design shown in Figure 2, a heat transfer analysis was conducted using computer programs developed for previous stage-two designs and modified as necessary to accommodate the new design. Requirements for the analysis were as follows:

- o No change in performance over chordwise-cooled design
- o No change in outer airfoil configuration
- o Same cooling airflow as chordwise-cooled design
- o Same maximum blade inlet temperature

The comparison of the thermal analyses for the chordwise trailing-edge design and the radial design is shown in Figure 3. Hole sizes and relative positions for each design are presented in Figure 4. The cooling flow area for the thermal calculations is based upon the minimum diameter opening for each case.

The metal temperatures presented for the chordwise trailing-edge design resulted from a two-dimensional analysis of an airfoil section located between the chordwise trailing-edge cooling holes and thus represent the maximum cal-

culated trailing-edge temperatures for this design. The metal temperature in the plane of the chordwise trailing-edge holes would be approximately 20°F lower due to the closer proximity of the cooling holes. The radial design does not have this trailing-edge temperature variation due to uniform conduction from the last (number six) hole to the trailing edge. However, as may be seen from Figure 3, the trailing-edge temperature distribution for the radial blade is higher at all points than for the chordwise trailing-edge hole design. This produces a bulk temperature for the radial blade that is 11°F above that calculated for the chordwise trailing-edge blade. However, due to the lower design stress for the radial blade as well as the elimination of the stress concentration factor associated with trailing-edge cooling holes, the calculated stress-rupture life was not reduced by the higher bulk temperature of the blade. This calculation was later substantiated by an actual engine test in which the radial-hole design showed at least a 3-to-1 improvement in life over the chordwise trailing-edge hole design.

Due to the selection of the radial-hole design as the Model Qualification Test (MQT) blade, additional engineering analysis over and above the original program was completed by General Electric. As part of this work, the thermal analysis of the radial-cooled design was done in more detail at different span height sections. Additionally, a stress analysis and creep-rupture life analysis were done using computer programs developed by General Electric. The results of these analyses are summarized in Figure 5 for the radial-hole blade at the pitch section.

Design Evaluation

As engine test experience was accumulated, the chordwise trailing-edge hole design evolved from a six-hole blade to an eleven-hole blade and, finally, to the nine-hole MQT blade. Changes in the number of holes and the hole positions along the trailing edge were made in order to improve cooling and to increase life. The MQT chordwise trailing-edge hole blade also incorporated other design features to improve performance and blade life, specifically, the addition of angel wings and skirts and a retilt of the blade in relation to the stacking axis. Briefly, the angel wings and skirts were intended to keep hot gases away from the cooling plates and were added to both the stage-one and stage-two high-pressure turbine blades. The blade retilt was incorporated to reduce the tensile stresses at the trailing-edge and was calculated to effect a reduction of 10,000 psi at 25% span. These features were also incorporated in the radial-cooled blade design. Figure 6 is a schematic view of the evolved radial-hole design, including the angel wings and shank skirts. Based upon improved life in endurance testing, the radial-hole design subsequently became the MQT design.

Materials Selection

The material specified for both of the original T700 high-pressure turbine blades was René 120, a nickel-base superalloy developed by General Electric. No problems were encountered with this material as used for the T700 parts; however, larger blades cast in the same material were shown to contain hot tears and relatively heavy microporosity. As a result, another alloy with properties similar to those associated with René 120 was developed by General Electric for use in all engine lines. The new alloy was a balanced/optimized René 120 composition with an addition of hafnium and was designated René 125. Initial casting studies showed the new alloy to have improved castability over Rene 120 in that the incidence of hot tearing and the tendency to form microporosity were substantially reduced, primarily due to the increased grain boundary strength imparted by the hafnium. Based upon these results René 125 was decided upon for use in the radial-cooled blade to preclude hot tearing in the thin wall areas associated with the trailing-edge cored hole. The engineering casting drawing was issued to permit the use of either René 120 or René 125 material with the final material selection to be based upon foundry yields and engine test results.

BLADE MANUFACTURE

The following sections detail the tooling approach used for the radial-hole blade, the casting process, and the dimensional results obtained on the completed castings, as well as the machining of the castings to the final configuration.

Tooling Approach

Precision investment casting of airfoil shapes requires the use of metal pattern equipment into which wax is injected to form individual, disposable patterns. For air-cooled turbine blading, air passage holes are generally formed using ceramic core bodies or individual fused-quartz tubes. In the case of the T700 turbine blades, the required hole sizes are so small that it is beyond the state-of-the-art to use ceramic cores. Consequently, small cored passages can be formed only through the use of quartz tubes, which must be precisely positioned within the wax pattern. Two basic tooling approaches have been developed over the years to address this requirement. The first approach developed involves direct injection of wax over the prebent tubes as placed in the core seats of the metal injection die. The second approach involves the injection of the wax over pull wires, the withdrawal of the wires, and the insertion or "stuffing" of the prebent quartz tubes into the cavities left by the removal of the wires. Both approaches can produce satisfactory results, and the selection is generally based upon factors such as the complexity of the cores, the size of the cores and the amount of bend in the cores.

The first tooling approach mentioned was used for the chordwise trailing-edge hole cooled hardware due to the requirement for a cast-in tip plenum, which is a feature that cannot be conveniently stuffed. A ceramic tip plenum core and four radial quartz cores were assembled into a core bundle as shown in Figure 7 and located in the wax injection die. Wax was then injected over the bundle to form the completed airfoil wax pattern. This approach turned out to be very costly in terms of material, labor, and scrap, and the core position in the resulting cast product was highly variable in true position. The primary problem was the stackup of tolerances starting from the hand assembly of the core bundle, the positioning of bundle in wax die, and the movement of cores during mold firing and metal pouring. These factors combined to produce a core position tolerance of about ±0.025 inch and, due to the thin blade design, a resulting minimum wall thickness of under .015 inch, as shown in Figure 8. A typical section through the tip plenum is shown in Figure 9, which illustrates the result of attaching the ceramic core to the quartz rod. Additionally, the foundry had a very low yield for the part (about 25%) due to nonfill around the ceramic core and breakout of the quartz tubes through the thin wall of the blade. This was particularly true of the leading-edge core. As a result, the cast-in plenum design was deemed to be unproducible and not acceptable for the radial-cooled

blade. Based upon the preceding discussion, it was decided to tool the radial blade with a solid tip and put the plenum in by an EDM operation.

Having eliminated the necessity for the ceramic tip core, the radial blade could be tooled to utilize the core stuffing approach described previously. The advantages of this approach were a reduced labor input as no core bundle assembly was required, the elimination of the ceramic core from the bill of materials, and a great improvement in hole position, to ±.010 inch at most positions. Additionally, nonfill problems at the tip and core breakouts were minimized, with the result that overall casting yields improved to about 85%. As a result of this tooling approach, casting costs were reduced significantly, and this reduction more than offset the additional cost due to EDM of the tip plenum.

Casting Process

Both the chordwise trailing-edge and radial-hole blades were cast using practically identical processes. Waxes were injected as described under Tooling with the gate wedge attached to the trailing-edge side of the shank. Wax tree assembly consisted of attaching the gate stubs to a runner bar and tying the runner bars together with a ceramic pour cup. A completed mold tree consisted of four runner bars with twelve blades per runner for a total of 48 blades per mold. After completion of mold building, each mold was dewaxed and fired. Preheated molds were individually poured in a conventional over-under vacuum furnace. After cooling, each mold was cleaned, identified, cut off, and processed through the complete foundry finishing cycle.

Foundry Results

As mentioned previously, the radial-hole blade showed a significant improvement in casting yield over that experienced for the chordwise trailing-edge hole blade. No problems were encountered in meeting drawing requirements for nondestructive inspection or grain size. Figure 10 illustrates typical grain sizes of the René 120 and the René 125 blades. As may be seen, the René 125 blade has a finer grain size than the René 120. This is due to lower process temperatures attainable with René 125, which reflects the reduced hot tearing tendency of this material compared to the René 120 alloy.

As part of the qualification process for each blade design, 15 pieces were cut up, and all dimensions were inspected. The inspection results were the basis for a probability study used to assure that future castings will meet all dimensional requirements within a 95% probability band. The important result of the probability study was that only nine relatively small changes had to be made to the casting drawing or casting tooling to assure that the overall process would produce acceptable parts. Additionally, several dimensions were required to

be checked at the foundry to assure adherence to the drawing requirements. Overall, the radial-hole blade tooling was very good and produced parts with a minimum of deviations from the original drawing.

Machining Of Castings

Finished castings were provided by the investment foundry to General Electric in order for machining, coating and inspection operations to be accomplished. All process operations for the radial-hole blade are listed in Table 1 for reference, side by side with the operation sequence for the chordwise trailing-edge hole blade. The operation sequences for both the blades are very similar. For the radial-hole blade sequence, it should be noted that the electrostream drilling of the chordwise trailing-edge holes has been eliminated as well as the cross-pin braze closure of the trailing-edge radial passage. Additionally, several inspection steps associated with the chordwise trailing-edge holes have been eliminated. The cost effect of these changes is discussed in the section entitled COST ANALYSIS.

No problems were encounted in EDM of the tip plenum in the radial-hole airfoil. Special tooling was provided to produce the actual cavity and a slash cut from the No. 6 radial hole to the plenum. (See Figure 5.) The purpose of the slash cut is to prevent the plugging of the No. 6 radial hole during the rubbing of the blade tip. A representative plenum was inspected by metallography, as was the cast-in plenum shown in Figure 9. Three sections were taken through the EDM plenum and analyzed at 40X magnification. A composite photograph of the midchord section is shown in Figure 11. Inspection results are listed in Table 2. Since the minimum wall thickness observed was .017 inch, the EDM plenum met all drawing requirements and was more consistent than the cast-in version.

As shown by Table 1, the process sequence for the radial-hole blade includes an airfoil polishing operation after machining and a waterflow inspection of the radial-holes to assure that they have not been plugged by the machining or polishing operations. The next operation is the coating of the airfoil with an aluminum vapor, a process which is called CODEP and is intended to protect the blade from hot corrosion during service. Following CODEP, the parts are aged, cleaned, polished, shot peened on the machined shank to improve fatigue properties, adjusted for proper airflow and inspected. These operations are part of the general process sequence for any General Electric blade and are not unique to the radial-hole blade.

QUALIFICATION OF DESIGN

The radial-hole blade design was qualified for use in the T700 engine on the basis of adherence to the applicable engineering drawing, bench fatigue tests and metallographic examinations. A strain-gaged gas generator test was included in the original work statement; however, the test was cancelled since sufficient engine test experience was obtained indicating the adequacy of the new design. A series of three 150-hour engine endurance tests was accomplished successfully. The results of each of these items are covered in the following sections.

Fatigue Testing

Airfoil fatigue strengths of the radial-hole blades were determined in the first flexural mode with the dovetail tightly clamped. All blades tested were finished machined and CODEP coated. Twelve blades were tested; six in René 125 material and six in René 120 material. Fatigue test data is listed in Table 3 and fatigue strength is summarized in Table 4.

For the René 125 radial-hole blade design, the average ten-million-cycle (10^7) fatigue strength was 58,000 psi, with failure occurring at the leading edge and convex root radii. This value compares very well with a Goodman diagram value of about 60,000-psi alternating stress for the René 125 material. Previous tests on the chordwise trailing-edge hole design showed a fatigue strength of 40,000 psi for the René 120 material, with failure occurring at the trailing-edge holes. Consequently, the radial-hole design represents an improvement of about 18 KSI and is able to take full advantage of the available material strength. As may be seen from Table 4, the radial-hole blade in René 120 material has a fatigue strength of 59,000 psi, which is equivalent to that for the René 125 material. Consequently, it can be stated that the improvement in blade fatigue life is due entirely to the change in design approach, not to the change in material.

Frequency distribution and nodal patterns were determined for two of the radial-hole René 125 blades and are presented in Figure 12. In order to accomplish this testing, each blade shank was welded to a solid steel block. The block was securely clamped in a fixture and the blade airfoil was excited in a vibratory mode. The resonant frequencies of the airfoil were determined for all modes below 30,000 Hz. No resonance of the airfoil occurred within this range at normal engine operating frequencies. Nodal patterns of resonating modes were determined by placing fine-grain sand particles on the blade airfoil and observing the resulting pattern. No significant difference between the radial-hole design and the chordwise trailing-edge hole design was observed. All patterns were considered to be normal and did not show any indication of future vibration or resonance problems for the stage-two blade.

Metallographic Inspection

Metallography was performed on selected radial-hole blades from the airfoil fatigue tests. Sections were taken through the tip plenum cavity, the blade airfoil and the blade shank for both the René 125 and the René 120 versions. As discussed previously, the tip plenum cavities were found to be acceptable. Airfoil sections taken near the platform and blade tip showed all six radial holes to be well equalized between the concave and convex sides of the airfoil. This is shown for the leading-edge near the platform in Figure 13A and near the tip in Figure 13B. Figure 13C shows the No. 6 radial hole at a section near the tip. Figure 13D is an enlarged, 400X view of the cast structure near the trailing-edge, where the freezing rate is quite rapid. This is evident in the fine carbide size (dark angular particles) and the dispersed areas of primary gamma prime (light areas). No inclusions or other defects commonly associated with the casting process were seen in any of the sections examined. Additionally, very little microporosity was seen.

Shank sections of the blades were taken radially at the leading and trailing-edges and longitudinally through the base. All shank sections were very sound and free of microshrinkage, which indicated that the basic gating and feeding system was adequate. Shank sections showed a larger grain and carbide size than that found in the airfoil. This is expected due to the relatively slower freezing rate in the shank and gate area. Figure 14 presents photomicrographs of the structure appearing in the shank near the gated area at two different magnifications and for both René 125 and René 120 materials. Figure 14B and Figure 13D illustrate the difference in carbide size and gamma prime distribution between the airfoil and the shank. Examination of shank cross-sections showed the hole pattern distribution in the longitudinal section of the shank to be slightly off on either side of centerline. This is due to the method of assembly of the wax pattern and core rods at the foundry and is not considered to be a problem.

All parts met appropriate grain size and intergranular attack (IGA) requirements, both in the as-cast state and after coating. The coating thickness of each finished blade was measured metallographically and found to be a total of 0.002 inch of additive and diffused layer thicknesses. No problems of any sort were observed in the sections examined, and all the blades were accepted for subsequent engine testing.

Gas Generator Test

This portion of the program was to have been conducted prior to actual engine testing. However, due to life problems with the chordwise trailing-edge hole blades, the radial-hole blade was tested as the MQT design. Based on the successful completion of the MQT test, the necessity for gas generator testing was eliminated.

Engine Test Evaluations

An engine test run of 150 endurance hours was necessary to qualify the radial-hole design for future production use in the T700 engine. The first set of radial-hole blades in René 125 material successfully completed this test by February 12, 1975. All of the blades were removed from the engine, nondestructively inspected by surface penetrant methods, and visually inspected under 20X magnification. No problems or signs of distress were observed. One blade was selected at random, sectioned, and evaluated metallographically. The results agreed with the visual inspection in that no problems were observed. An analysis of coating diffusion layers showed the blades to be running quite cool, as no additional diffusion of the layer had taken place.

Based upon the excellent results of the first engine test, the set of René 125 blades with one replacement was given an additional 150-hour endurance test for a total of 300 endurance hours and 405 total hours. Metallographic examination of another blade again showed no deleterious effects and no signs of distress. This set of blades was also used for an overtemperature test and ran with a gas temperature of 145°F over the rated value for over 5 minutes. Other engine testing of the radial-hole blade design included the use of René 125 blades on the official LCF engine, where a total of 1750 low-cycle fatigue cycles was completed in a total of 416 hours. Again, no problems were observed visually or metallographically after completion of the test. The René 120 blades were also run and completed 128 endurance hours without any difficulties before the test was discontinued due to other problems. All test results are summarized in Table 5 for the radial-hole blades.

COST ANALYSIS

The original program proposal predicted an average cost reduction of $177 per engine for 3300 sets of radial-hole turbine blades. Based on the results of this program, the achieved cost savings was calculated to be an average of $215 per engine for 3300 sets and $197 for 4700 sets. Calculations are based on learning-curve values established for the design-to-cost clause of the T700 contract and are in 1974 dollars.

To properly evaluate costs, it is necessary to track the changes in blade design and the associated cost increase (or decrease). This is done in Table 6, where it can be seen that the material costs associated with the cast-in tip plenum were high due to the high scrap rate at the foundry. Comparative costs are based upon steps 4 and 5 in Table 6, where both blades have EDM plenums. It must be noted that the chordwise trailing-edge blade has evolved in design up to step 4 in parallel with the radial-hole blade. Therefore no cost increase for the skirts and angel wings can be assigned to the radial-hole design. Consequently, the cost reduction attributable to the radial-hole blade is due to the elimination of the drilled trailing-edge holes and the cross-pin brazing operation (labor cost) less the cost of the two additional radial holes (material cost). This is based upon the 250th engine set cost and translated into a single blade cost. Table 7 compares the figures on an engine set cost basis and establishes a predicted average cost at various production quantities using standard learning-curve techniques.

CONCLUSIONS

All objectives of the original program were met or exceeded for the complete manufacture of the stage-two turbine blade. A cost reduction of $215 per engine set versus the goal of $171 was achieved based on a total production of 3300 engine sets. In addition to the achieved cost reduction, the radial-hole blade has shown a significantly increased life with no increase in cooling flow required and with no performance loss. The radial-hole blade in René 125 material has been designated the official MQT blade and will be the standard production item on the future T700 engines.

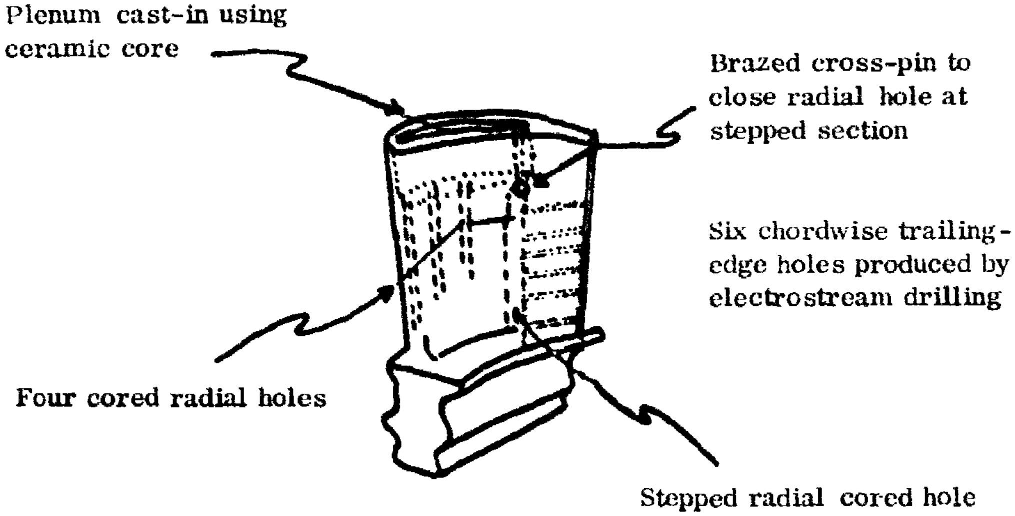


Figure 1. Schematic View Of Original T700 Stage-Two Turbine Blade Showing Salient Features

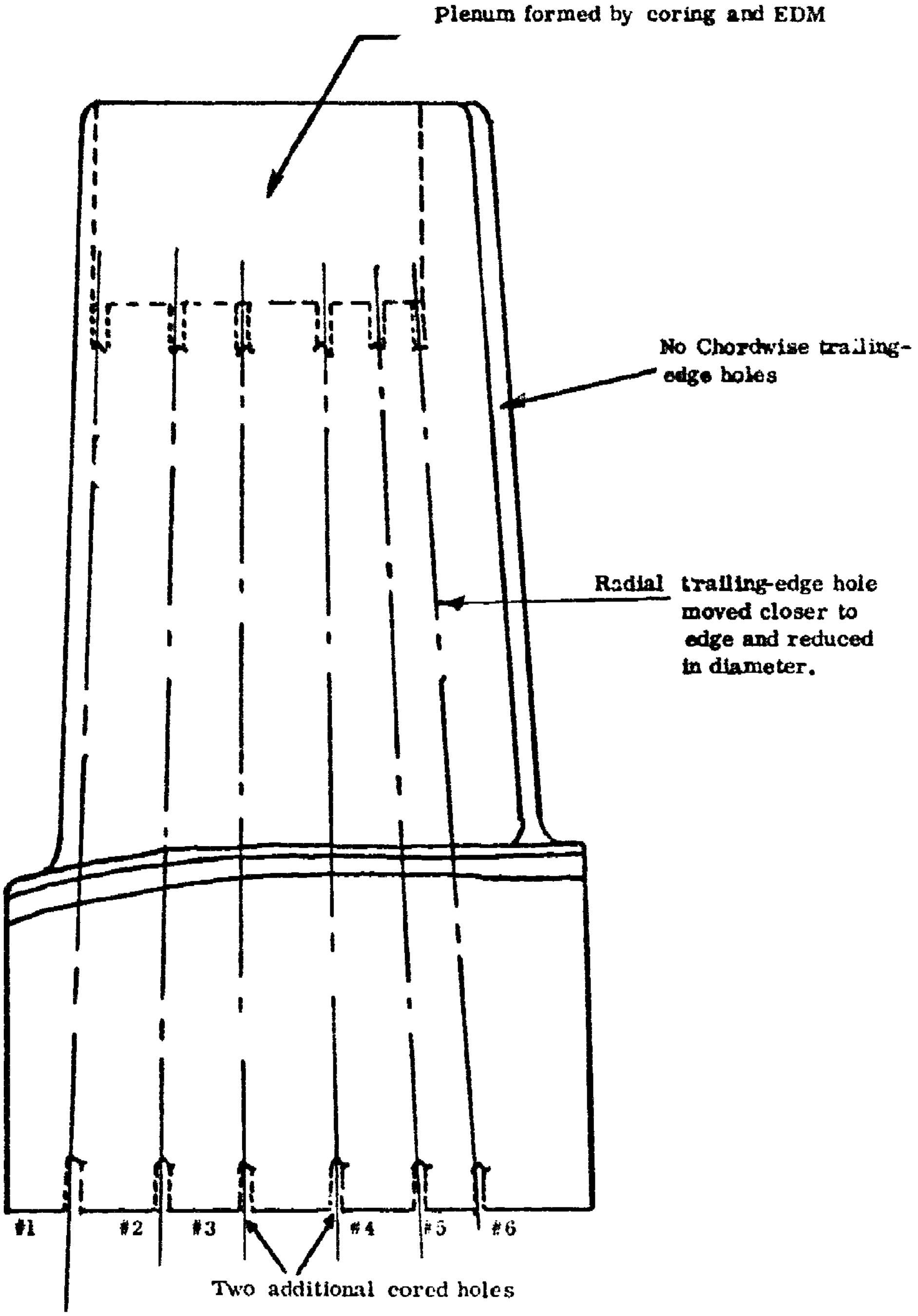


Figure 2. Schematic View Of Proposed All-Radial-Cooled T700 Stage-Two Turbine Blade

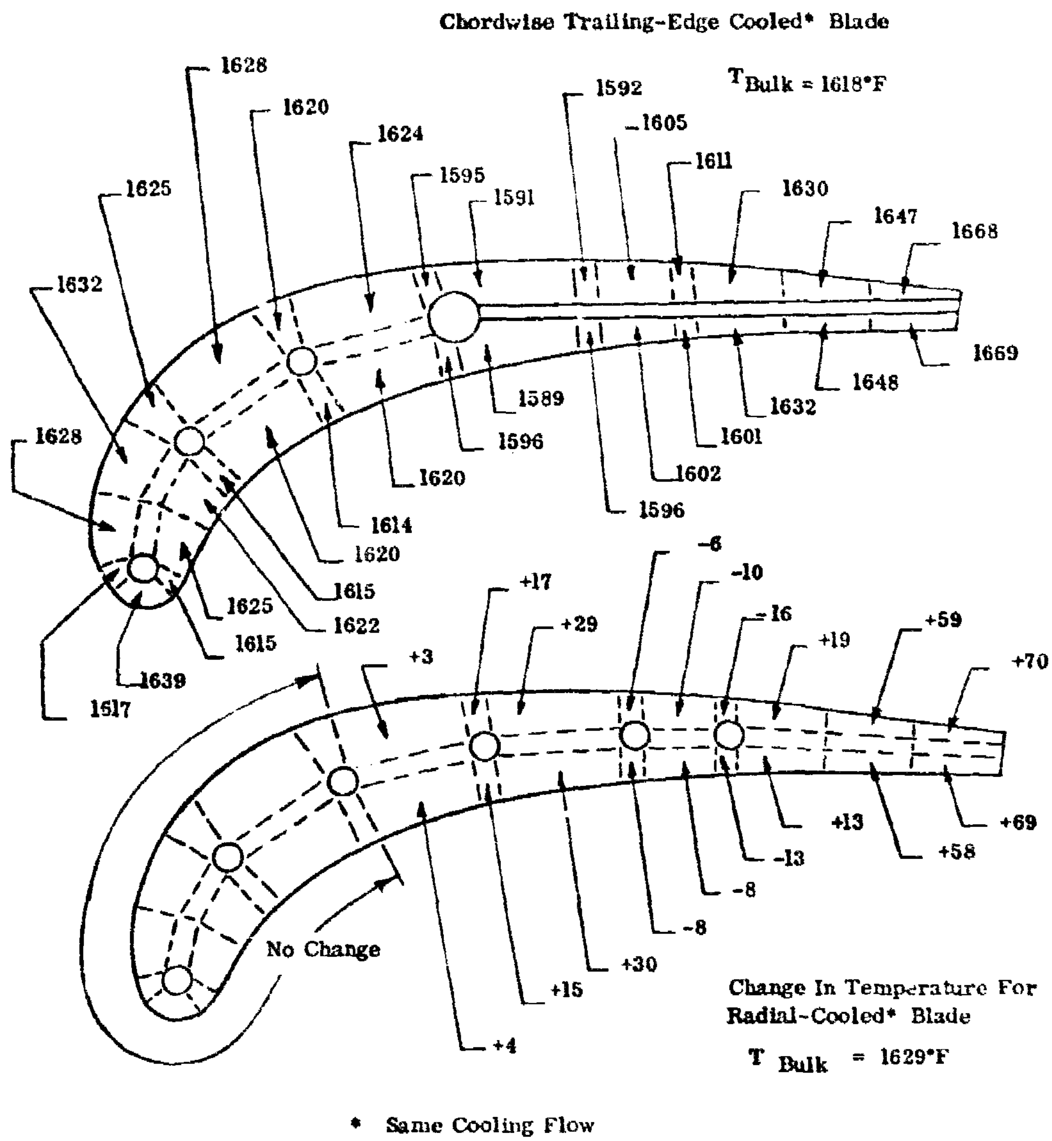
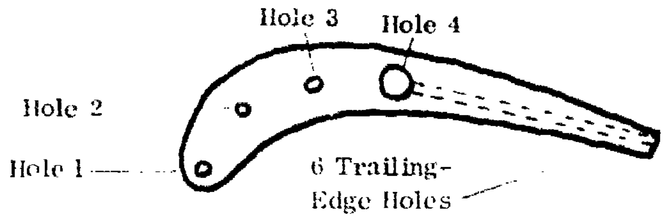
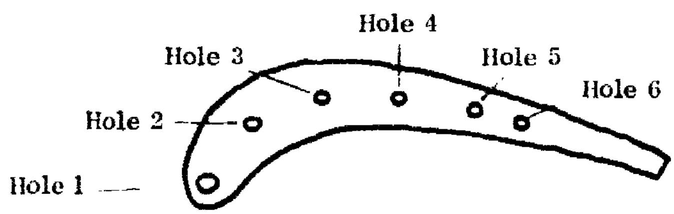


Figure 3. Calculated Temperature Distribution For Stage-Two Blades



Chordwise Trailing-Edge-Cooled Design

Hole 1	.0255 - .0225 inch diameter
Hole 2 & 3	.0195 - .0165 inch diameter
Hole 4	.0315 - .0285 inch diameter
Trailing edge holes	6 Holes .0125 - .0085 inch diameter



Radial-Cooled Design

Hole 1	.0255 - .0225 inch diameter
Hole 2 - 6	.0195 - .0165 inch diameter

Figure 4. Comparison Of Cooling Hole Sizes For Chordwise Trailing-Edge And Radial-Cooled Blades

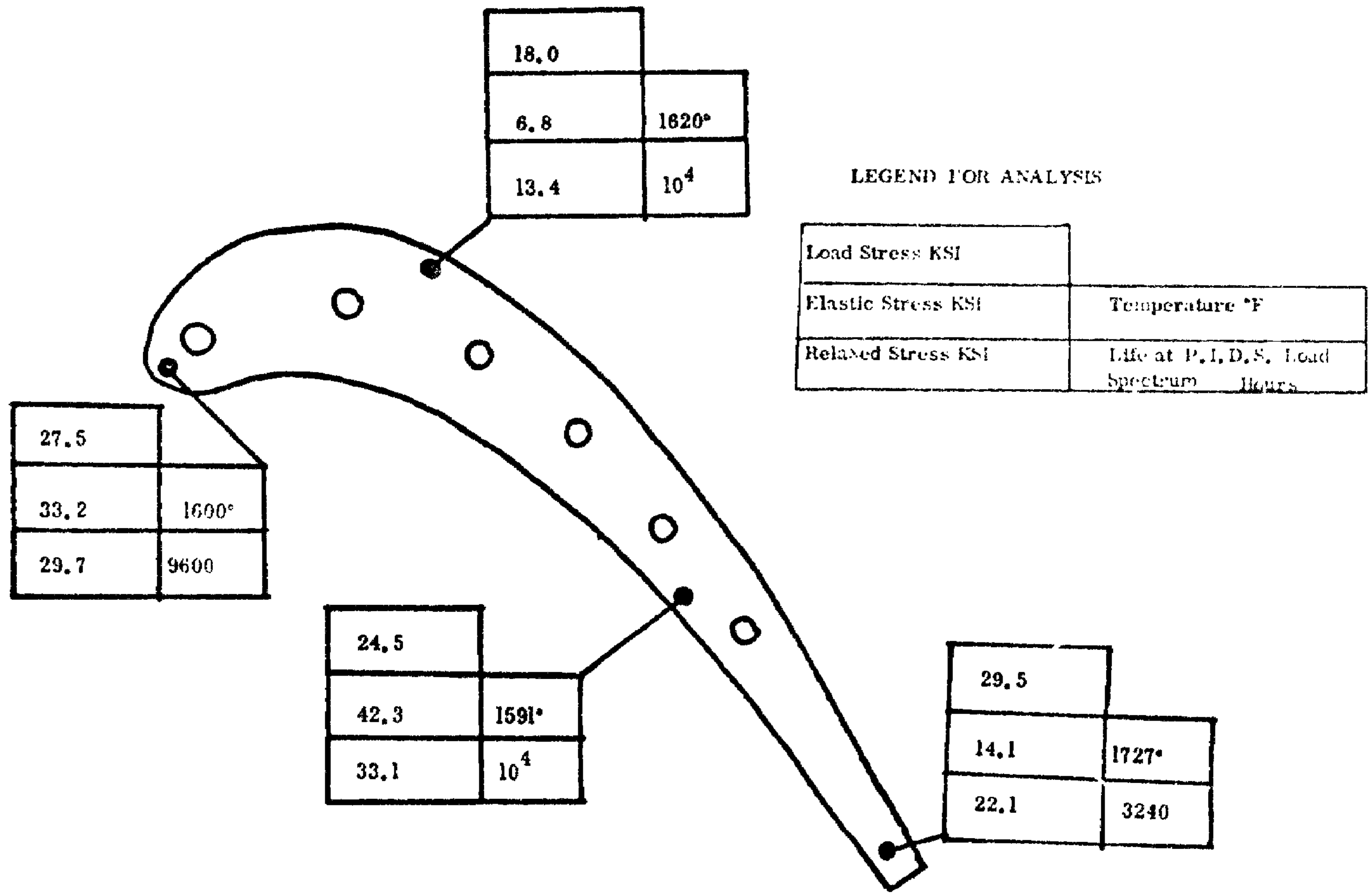


Figure 5. Summary Of Engineering Analysis For Stage-Two Radial-Cooled Blade, Pitch Section, René 125 Material

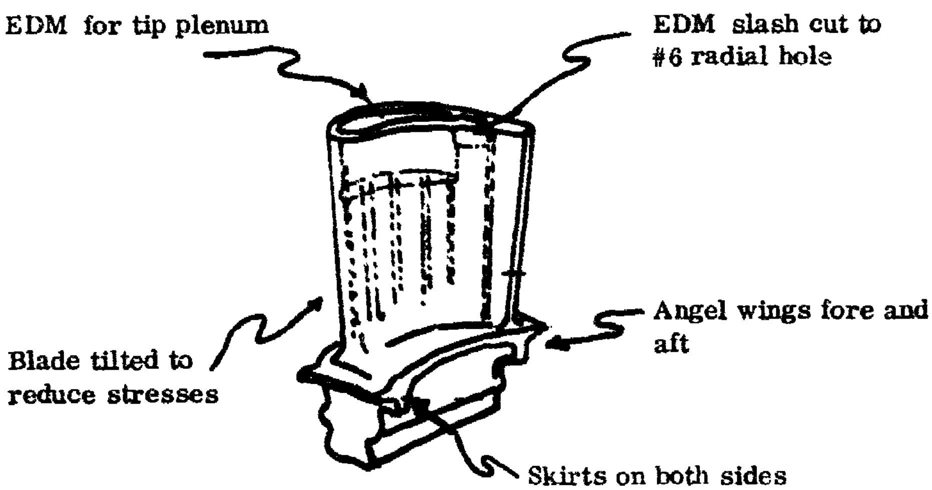


Figure 6. Schematic View Of MQT-Design Radial-Cooled Stage-Two Turbine Blade

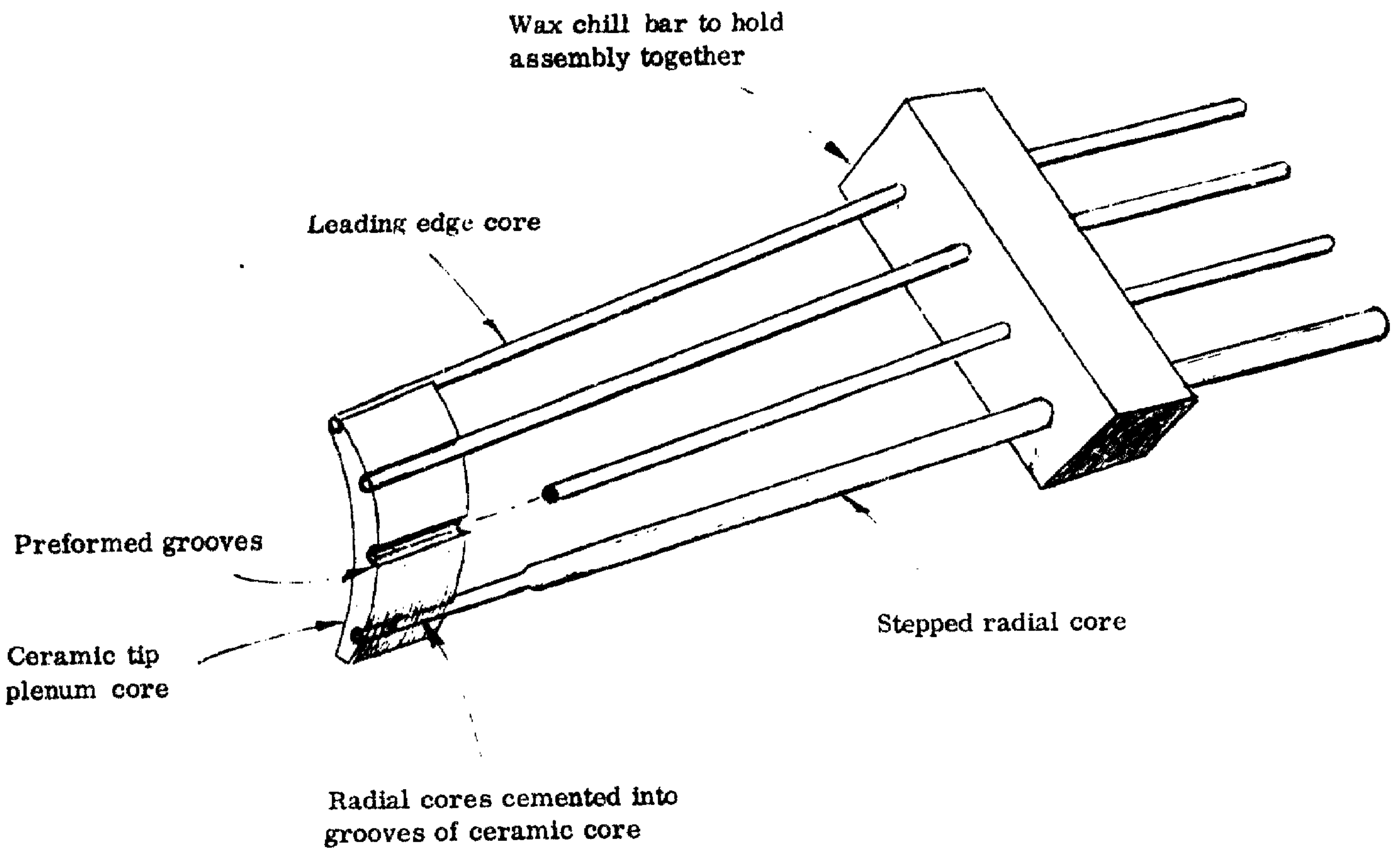


Figure 7. Schematic Of Core Bundle Assembly For Chordwise Trailing-Edge-Cooled Blade
(Not to Scale)

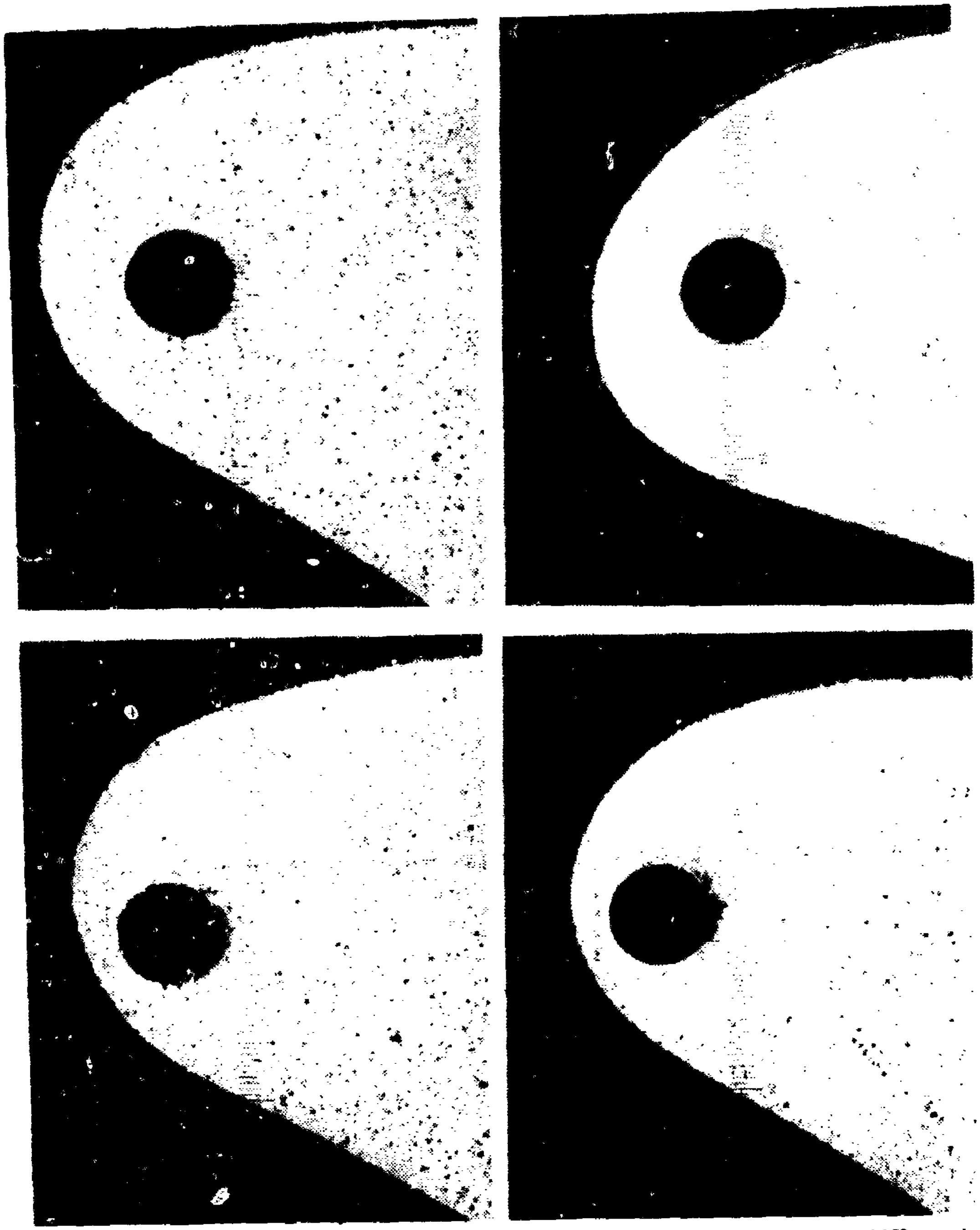


Figure 8. Variability In Wall Thickness At Leading Edge Of Two Different Chordwise Trailing Edge-Cooled Blades; Root Section On Left, Tip Section On Right (Original Magnification 40X, Reduced 14% On Reproduction)

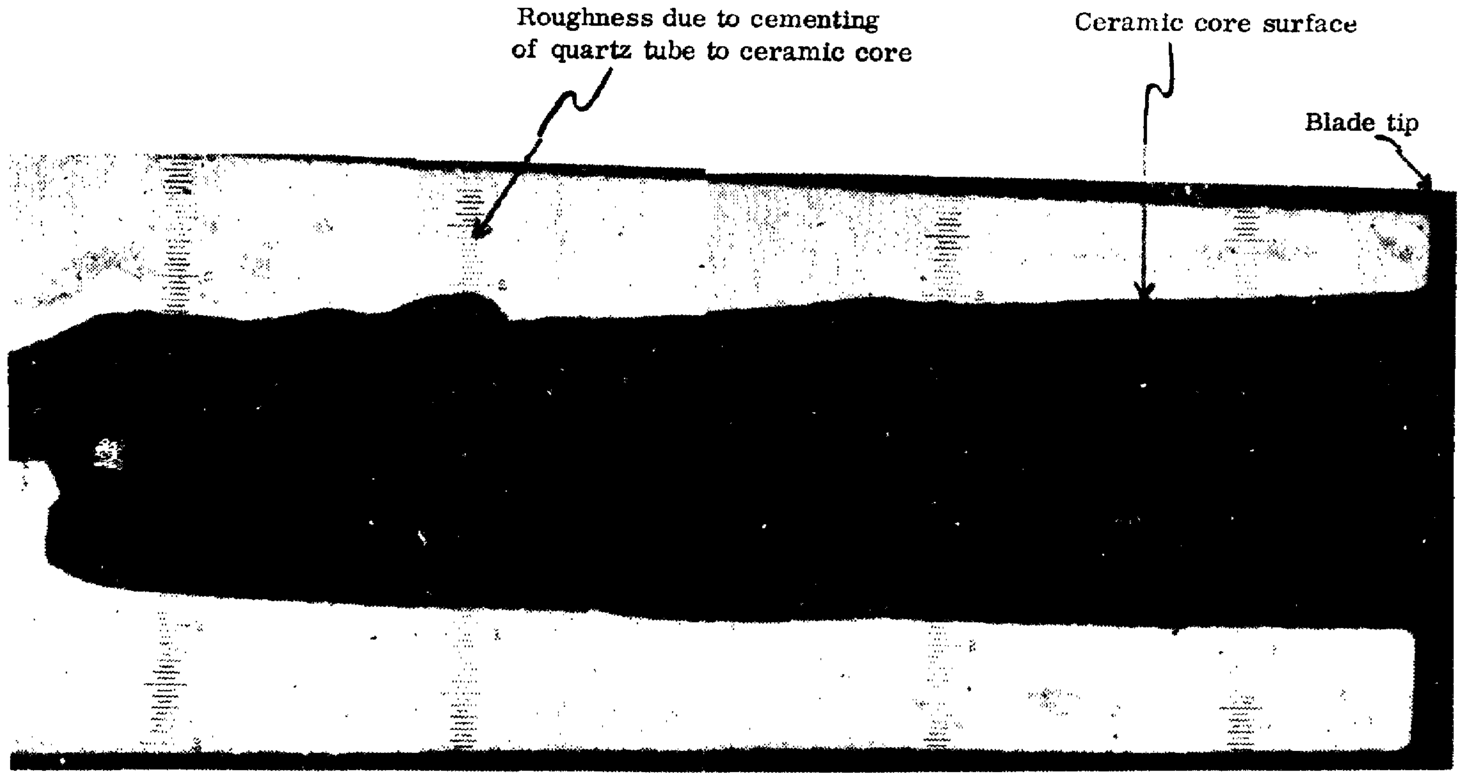


Figure 9. Metallographic Section Through Nu' ›er-Two Hole And Cast Tip Plenum Of Chordwise Trailing Edge-Cooled Blade (Magnification 40X, Reduced 20% On Reproduction)

Figure 10A

Convex Side

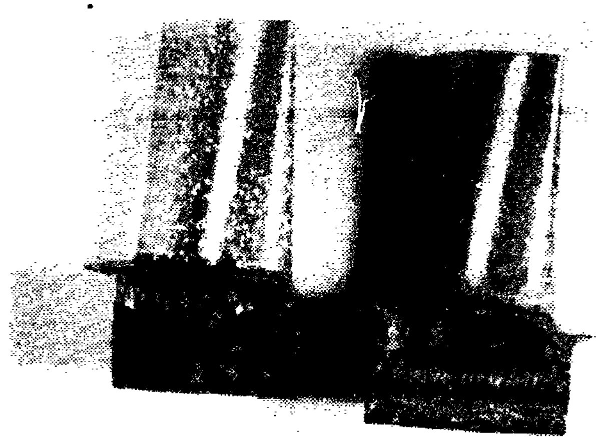


Figure 10B

Concave Side

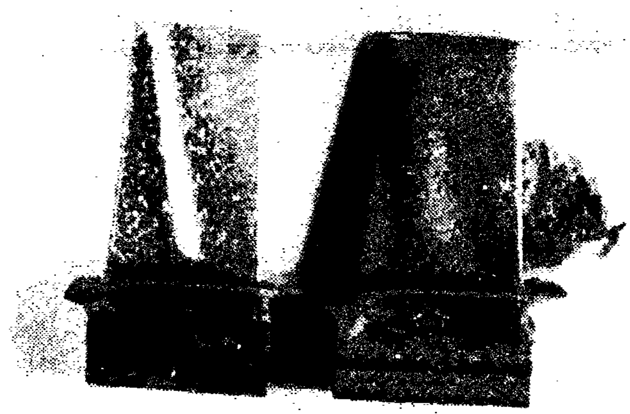


Figure 10. Comparison Of Grain Sizes For Radial Blade In René 120 (On Left) And René 125 Materials (Magnification 1.4X)

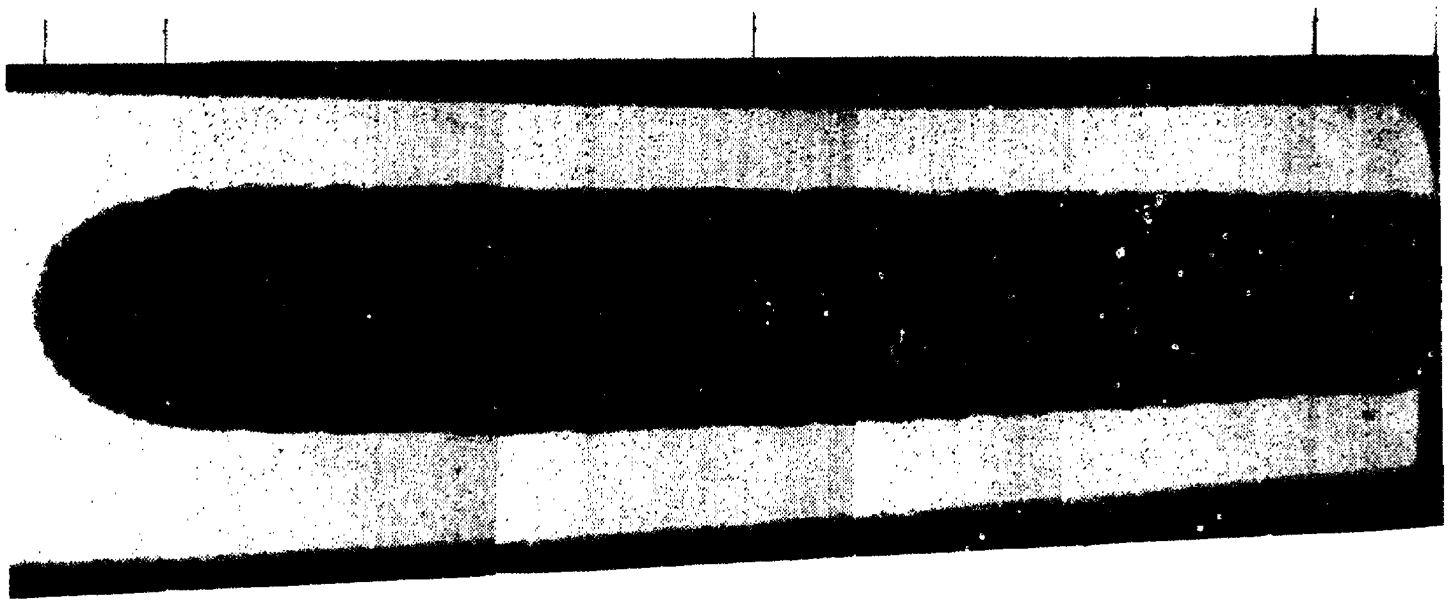


Figure 11. Cross-Section of Radial Blade Through EDM Tip Plenum Cavity, Aft Looking Forward (Original Magnification 40X, Reduced 30% On Reproduction)

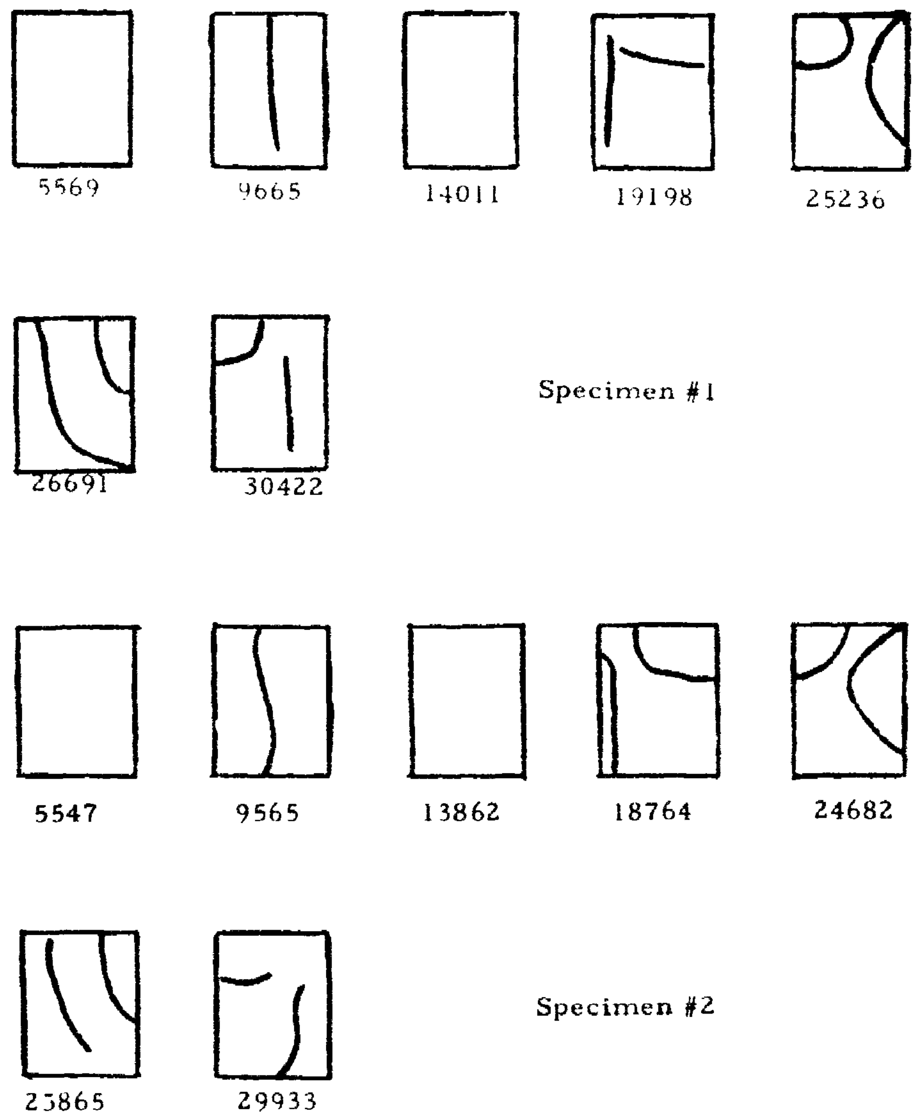


Figure 12. Frequency Distribution For Radial-Cooled Blades
Nodal line patterns shown starting from the lowest frequency in Hertz are First Flex, First Edge, First Torsion, Second Flex, Second Torsion, Two Stripe -1 and Two Stripe -2. Leading edge of blade is on the left for each case

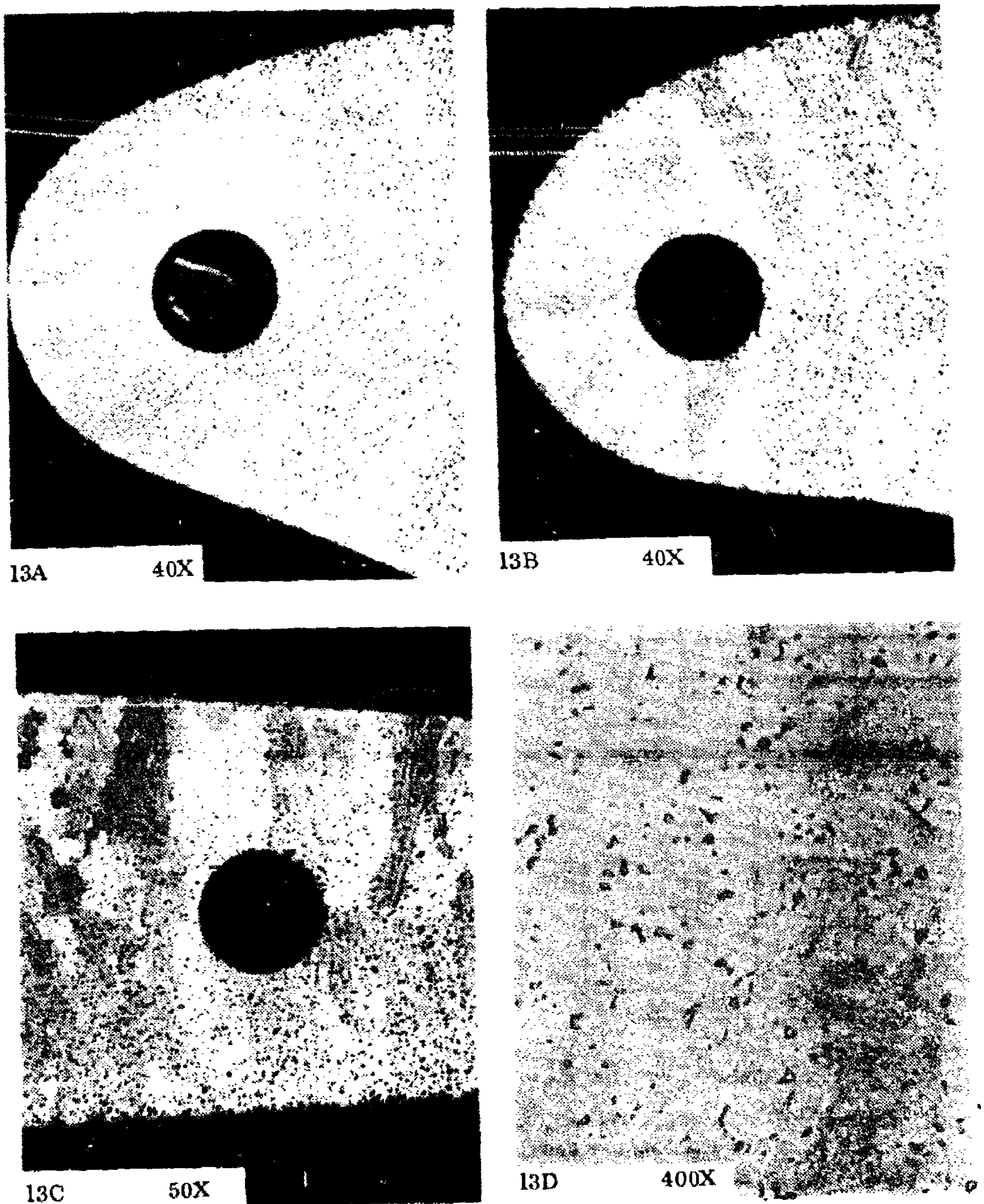


Figure 13: Photo Micrographs Of Airfoil Sections In René 125 Radial-Cooled Blade (Original Magnification As Shown, Reduced 14%)

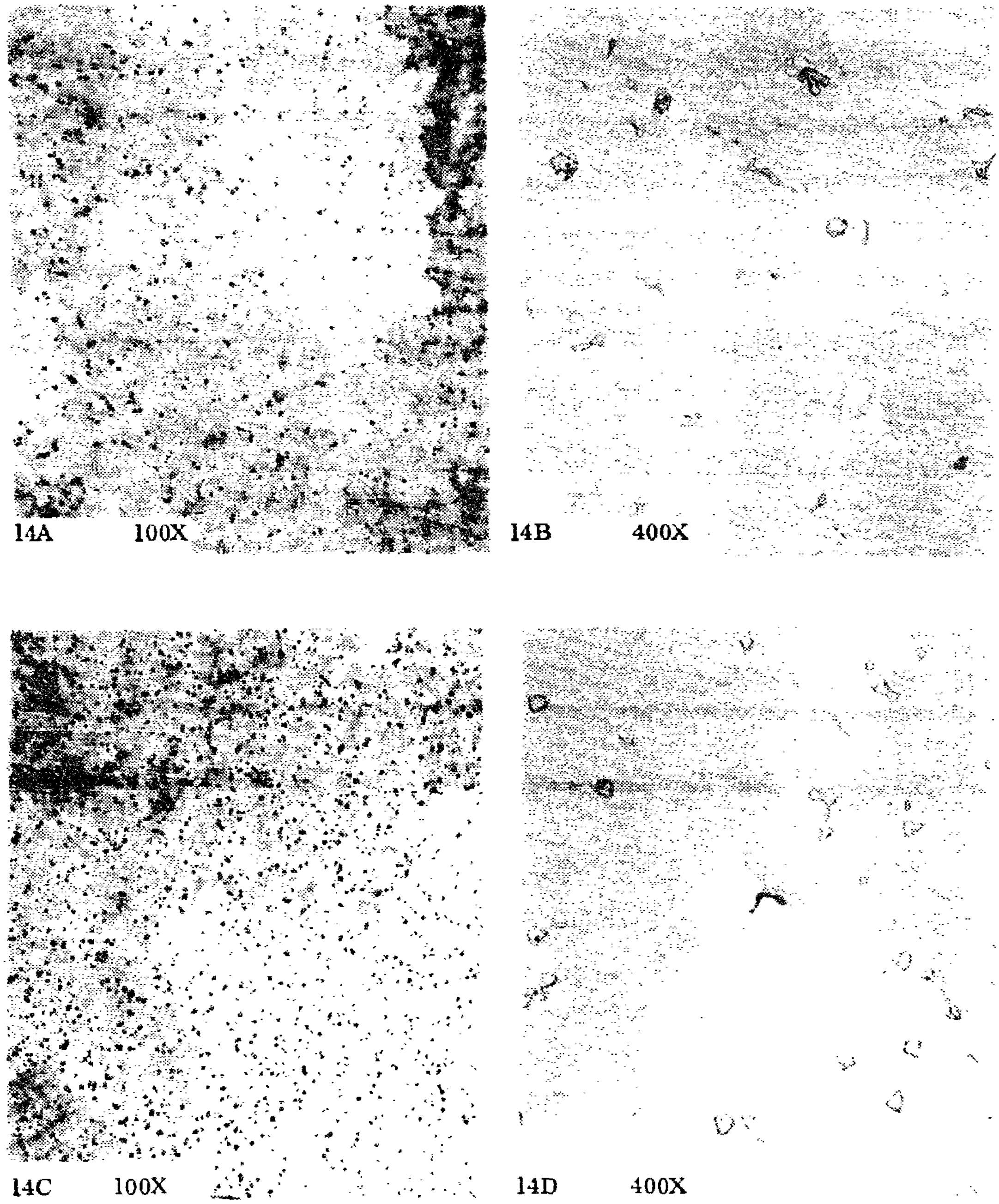


Figure 14: Photo Micrographs Of Shank Structures In Radial-Cooled Blades, René 125 At Top, René 120 At Bottom (Original Magnification As Shown, Reduced 14% On Reproduction)

Table 1

Operation Sequence for Stage-Two Turbine Blades

Radial-Hole Blade	Chordwise Trailing-Edge-Hole Blade
Rhodine Leach	Rhodine Leach
-	E.S. Drill Trailing-Edge Holes
EAG Trailing-Edge	EAG Trailing-Edge
-	X-ray Trailing-Edge Holes
-	Inspect
Grind Shank	Grind Shank
Mark Serial Number	Mark Serial Number
EDM Tip Plenum	EDM Tip Plenum
Polish Airfoil	Polish Airfoil
Inspect Shank And Cavity	Inspect Shank And Cavity
Fluorescent Penetrant Inspect	Fluorescent Penetrant Inspect
Degrease	Degrease
Waterflow And Inspect	Waterflow And Inspect
Freon Clean	Freon Clean
Seal Holes	Seal Holes
CODEP	CODEP
Ultrasonic Clean	Ultrasonic Clean
Inspect	Inspect
Heat Treat-Age	Heat Treat-Age
Polish	Polish
Shot Peen	Shot Peen
Waterflow	Waterflow
Airflow, Swage Holes	Airflow, Swage Holes
Weigh, Mark	Weigh, Mark
Final Inspect	Final Inspect

Table 2

Analysis Of Radial Blade With EDM Tip Plenum

Location	Plenum Depth, Inch	Wall Thickness, Inch *		
			Concave	Convex
Leading Edge	.319	Top	.0209	.0230
		Mid	.0193	.0344
		Bot	.0193	.050
Min. Wall			.0170	
Mid Chord	.2915	Top	.0198	.0180
		Mid	.0180	.0208
		Bot	.0215	.0276
Trailing Edge	.255	Top	.0278	.0210
		Mid	.0246	.0195
		Bot	.0240	.0257

* Thickness measured as follows:

(a)	Top	.025 inch from tip.
(b)	Bottom	.025 inch up from bottom of plenum.
(c)	Middle	Midway between above points.

Table 3

Fatigue Test Data For Stage-Two Blades

Part No.	Frequency (Hz)	DATE* (Mils)	Run Time (Min)	Cycles (Million)	Failure Location
6034T93P02	4834	30	6	1.7	Leading edge
All-Radial-	4900	27.5	32	9.2	Convex - Fillet
Hole	4896	27.0	40	10	None
René 125	4854	27.5	36	10	None
	4917	30.0	40	10	None
	5091	32.5	10	2.6	Convex - Fillet
	4915 avg.	28.7			
6034T93P04	5105	30	33	10	None
All-Radial-	5114	32	13	4	Convex
Hole	5095	30	11	3.4	Trailing edge
René 120	5155	28	33	10	None
	5109	30	12	3.7	Convex
	5128	28	33	10	None
	5118 avg.	29.6			
6032T39P01	4671	20	2	.6	TE at hole
Chordwise	4730	17.5	35	10	None
T.E. Hole	4666	20	6	1.7	TE at hole
René 120	4724	17.5	35	10	None
	4755	20	8	2	TE at hole
	4709 avg.	19.0			

* Double Amplitude of Trailing Edge

Table 4

Summary Of Fatigue Test Results For T700 Stage-Two Turbine Blades

Cooling Type	Material	Fatigue Strength, KSI
Chordwise Trailing Edge	René 80	40
Chordwise Trailing Edge	René 120	38
Radial Hole	René 125	58
Radial Hole	René 120	59

Table 5

Engine Test Data For Stage-Two Radial Blade

Engine Build	Material	Date Complete	Endurance Hours	Total Hours
009-1A To 009-2D	René 125	2-12-75 5-14-75	300*	405*
010-2A/2C	René 125	7-17-75	1750 LCF Cycles	416
009-3A	René 120	8-11-75	128	183**
009-4C	René 125	9-18-75	Overtemperature Test $T_{4.1}$ was 145°F over Intermediate Rated Power	0.09*

* Two 150-Hour Endurance Runs And Time In Overtemperature Test

** Test Discontinued For Problems Not Related To Stage-Two Blade

Table 6

T700 Stage-Two Blade Design And Cost History

A. Design History:

	Number Of Radial Cored Holes	Number Of T. E. Cooling Holes	Tip Cavity	Angel Wings And Shank Skirts	Use
Step 1	4	6	Cast	None	XT
Step 2	4	11	Cast	None	YT
Step 3	4	9	Cast	Yes	MQT
Step 4	4	9	EDM	Yes	MQT
Step 5	6	None	EDM	Yes	MQT

B. Cost History:

	Material	Labor	Total
Step 1	$43.21	$36.39	$79.60
Step 2	$43.21	$29.56	$82.77
Step 3	$45.40	$37.83	$83.23
Step 4	$38.00	$39.56	$77.56
Step 5	$39.50	$29.91	$69.41

Notes:
(a) Material Cost Does Not Include Materials Purchasing And Handling Expense.
(b) Figures Quoted Per Single Blade At 250th Engine Unit.

Table 7

Comparison Of Blade Cost Per Engine Set

Chordwise Trailing Edge Cooled Vs All-Radial-Cooled Designs

ENGINE QUANTITY COST BASIS	ORIGINAL DESIGN SHOP COST	NEW DESIGN SHOP COST	DELTA SHOP COST
250th Unit	$2, 947*	$2, 638**	$-309
500 Average	$3, 306	$2, 959	$-347
1000 Average	$2, 777	$2, 486	$-291
3300 Average	$2, 056	$1, 841	$-215
4700 Average	$1, 881	$1, 684	$-197

* Material = $1, 444
Labor = $1, 503

** Material = $1, 501
Labor = $1, 137

Notes: The learning curves used are consistent with the design-to-cost procedures established for the T700 and approved by the Army.

Shop costs do not include materials purchasing and handling expense.

Figures quoted are in 1974 year dollars.